Figures of merit for testing modifications to GR

WFIRST meeting 2-3rd Feb 2011

Outline

- Modeling modifications to GR
- Effect of modification to GR on observations
- Combining observations
- Including systematics
- Figures of merit
- Some thoughts

Constraints on gravity

- Terrestrial and Solar System
  - Lab tests on mm scales
  - Lunar and planetary ranging
  - Binary pulsar timing

- Galactic
  - Galactic rotation curves and velocity dispersions
  - Satellite galaxy dynamics

- Intergalactic and Cluster
  - Galaxy lensing and peculiar motions
  - Cluster dynamical, X-ray and lensing mass estimates

- Cosmological
  - Late times: comparing lensing, peculiar velocity, galaxy position, ISW correlations
  - Early times: BBN, CMB peaks

Modifications to GR

- Alternative origin for cosmic acceleration to Λ or dark energy fluid
  - Alter Friedmann and acceleration equations at late times and on cosmic scales

$$stuff + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + 3P_m)$$

- No thoroughly compelling theories, but instructive models exist
  - Examples: DGP , f(R), scalar tensor gravity
- Have to satisfy tests of gravity on all scales
  - Recover GR in high density regions (chameleon mechanism)
  - Scales at which transition occurs model dependent (kpc-Mpc?)
- Use phenomenological model rather than specific theories to
  - understand limits of current data
  - Provide benchmark for future survey goals

Modeling modifications to GR

- Can modify both homogeneous expansion (to create accelerated expansion in H(z)) and metric perturbations

- In GR, H(z) plus matter census determine perturbation evolution
  - Metric potentials ϕ and ψ,

$$ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2$$

  - density and velocity perturbations $\delta = \frac{\delta\rho}{\rho}$ and $\theta = \nabla.v$

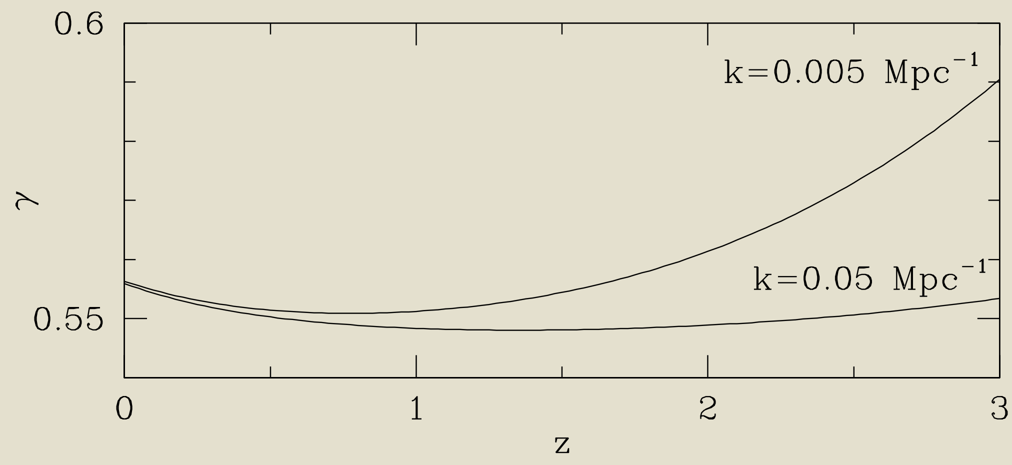
- Modifications to GR alter the relationship between perturbations and background
  - Relation between ϕ and ψ, and δ and θ
  - At late times and cosmological scales, coincident with acceleration

Changing the growth rate

- The "gamma" parameter , γ
  - used by ISWG report
  - Describes change to the growth rate in CDM density perturbation

$$f \equiv \frac{d\ln\delta_c}{d\ln a} \equiv \Omega_m(a)^\gamma$$

  - γ~0.55 in accelerated era



Changing the relationship between ϕ and ψ

- Many theories of gravity have similar phenomenological properties

- A modification to Poisson's equation, Q

$$k^2\phi = -4\pi G Q a^2 \rho \Delta$$

Q≠1: can be mimicked by
– additional (dark energy?) perturbations,
– modified dark matter evolution

- An inequality between Newton's potentials, R

$$\psi = R\phi$$

R≠1: not easily mimicked.
– potential smoking gun for modified gravity?
– Significant stresses exceptionally hard to create in non-relativistic fluids e.g. DM and dark energy.

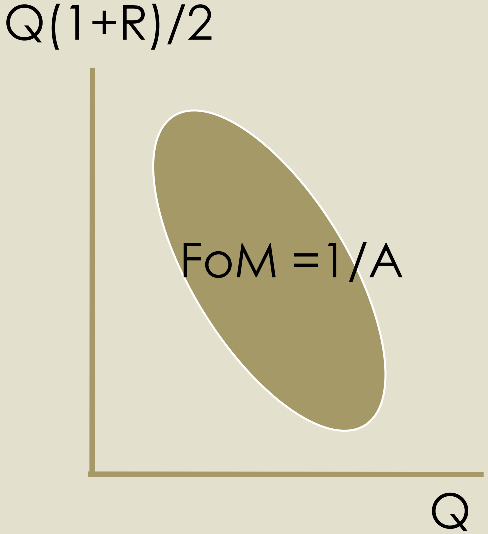
Modeling and Figures of Merit

- Simple modeling
  - scale independent, but allow simple redshift evolution
- Figures of merit in γ
  - 95% confidence limit in γ

$$\gamma(a) = \gamma_{GR}(a) + \Delta_\gamma \qquad \Delta_\gamma(z) = \Delta_{\gamma 0} a^s$$

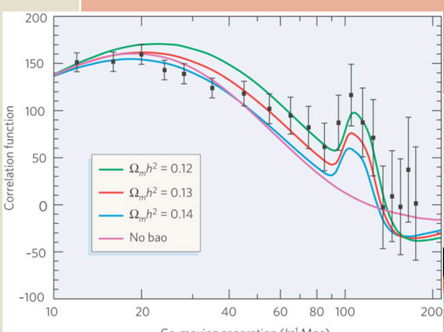
- Figures of merit in Q and R
  - Area of 95% c.l. in Q and Q(1+R) plane

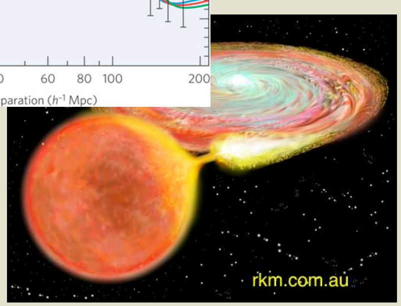
$$Q(a) = 1 + (Q_0 - 1)a^s, \qquad R(a) = 1 + (R_0 - 1)a^s$$

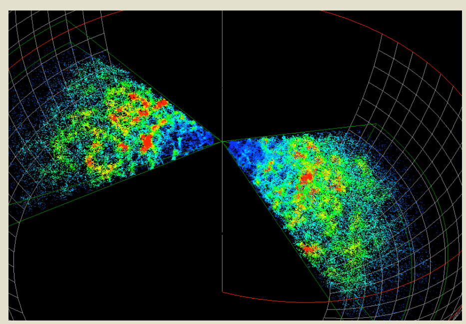


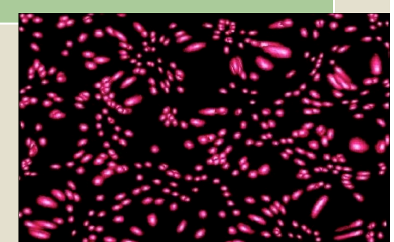
Three groups of extra galactic observations for testing gravity

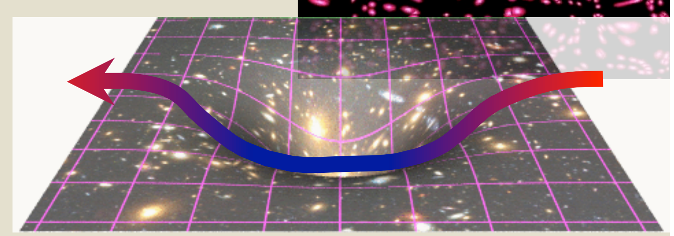
I: Background expansion	II: Growth, up to some normalization	III: Growth directly
CMB angular diameter distance	Galaxy autocorrelations	CMB ISW autocorrelation
Supernovae luminosity distance	Galaxy – ISW x-corrln	Weak lensing autocorrelation
BAO angular scale	Xray and SZ galaxy cluster measurements	Peculiar velocity distribution/ bulk flows
	Ly-alpha measurements	







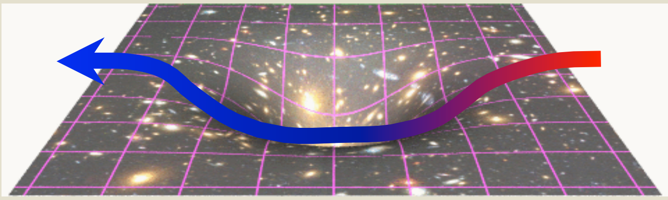




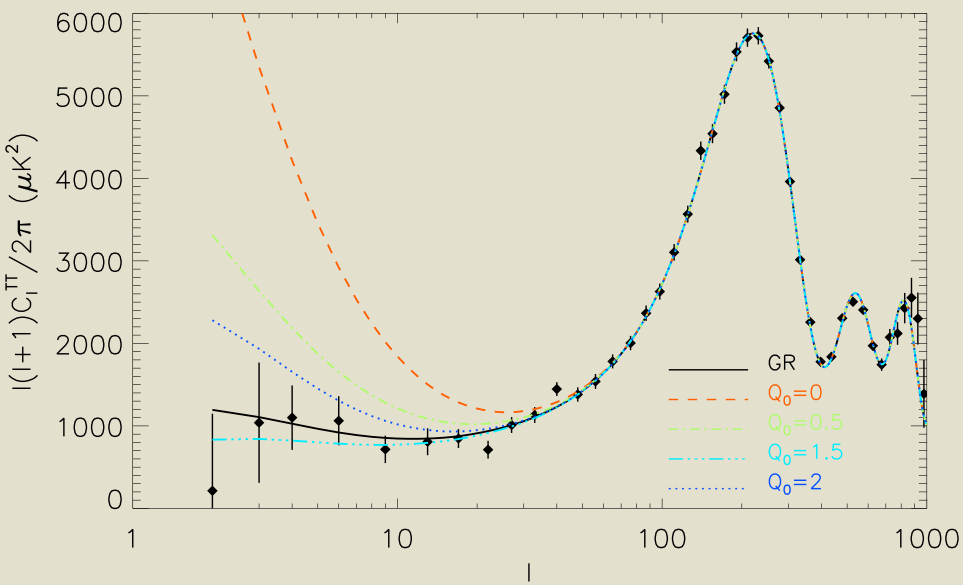
CMB autocorrelations

- Late time modifications => change in ISW on large scale

$$\frac{\Delta T}{T} \propto \dot{\phi} + \dot{\psi}$$



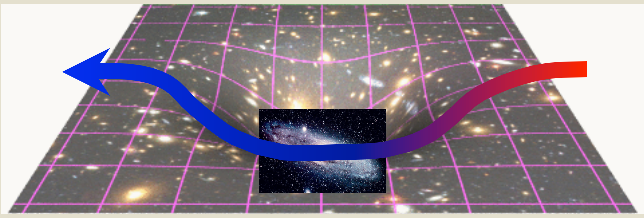
- Increasing Q or R boosts growth of LSS
  - Q and R degenerate
  - opposite effect to acceleration
    - CMB cools, ΔT reduced, and could be <0
    - $C_l \sim \Delta T^2$ falls then increases (not monotonic)



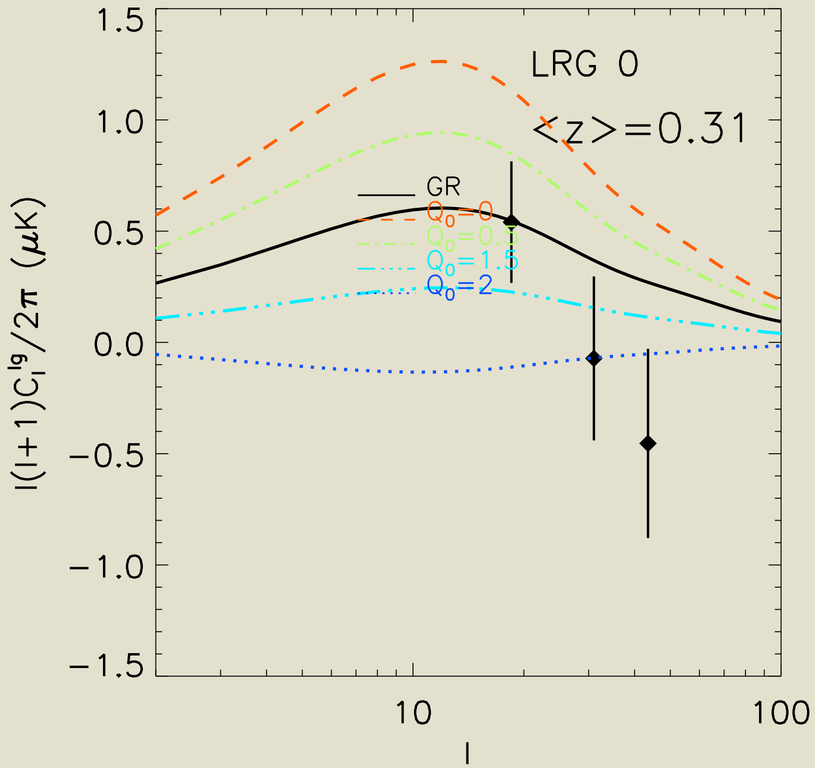
Rachel Bean WFIRST February 2011

ISW-galaxy correlations

- Monotonic in Q & R
  - Galaxy position $\delta \sim \phi$
  - ISW dependent on $d(\phi+\psi)/dt$
- Boosting potential (Q,R>1)
  - Suppresses ISW
  - Reduces ISW-galaxy correlation
  - Since ΔT can become negative can lead to anti-correlation



ISW-galaxy correlation for low z LRG sample



Weak lensing correlations

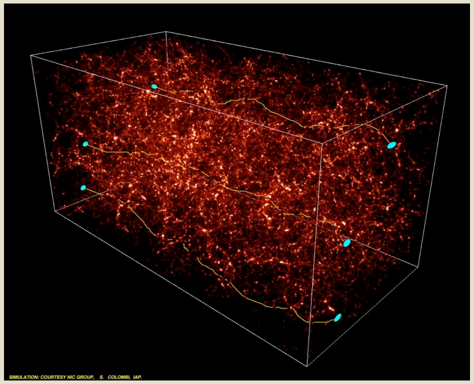
- Lensing deflection angle

$$\alpha = -\nabla_{\perp}(\phi + \psi)_{2d}$$

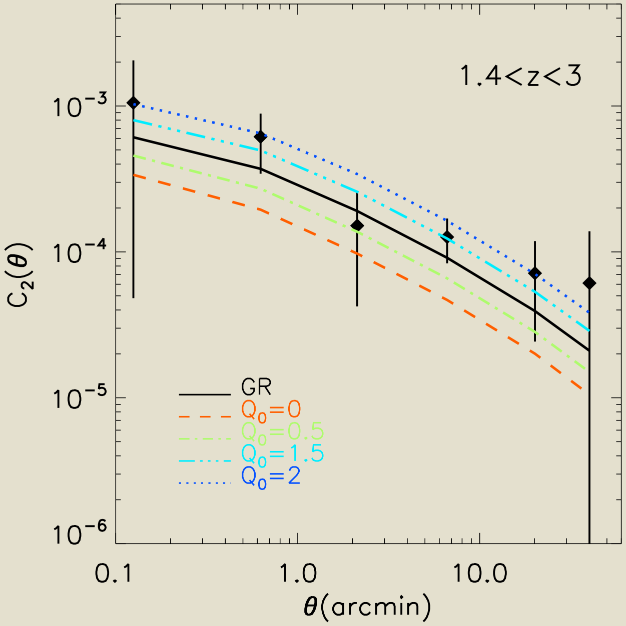
- Magnification, convergence

$$\kappa = -\frac{1}{2}k^2(\phi + \psi)$$

- Boosting potentials (Q,R>1) boosts lensing amplitude
  - Monotonic and degenerate in Q (1+R)

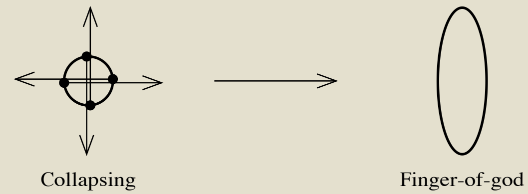


Lensing correlation for high z sample



Peculiar velocities and bulk flows

- Coherent peculiar motions of galaxies ($\Theta=\theta/aH$) can be statistically estimated from redshift space distortions



$$P_g^{obs}(k,z,\mu) = \left[P_{gg}(k,z) + 2\mu^2 P_{g\Theta}(k,z) + \mu^4 P_{\Theta\Theta}(k,z)\right] e^{-k^2\mu^2\sigma_v^2(z)}$$

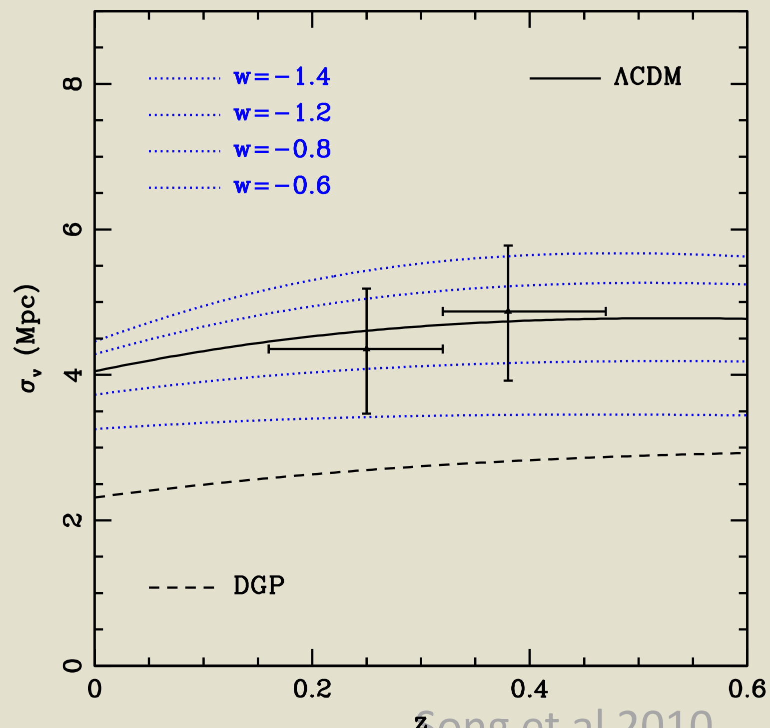
- 1D velocity dispersion

$$\sigma_v^2(z) = \frac{1}{3(2\pi^2)} \int dk P_{\Theta\Theta}(k,z)$$

- Complementary dependence on ϕ and ψ from galaxy position, lensing and ISW

$$\frac{d(a\theta)}{dt} = k^2\psi$$

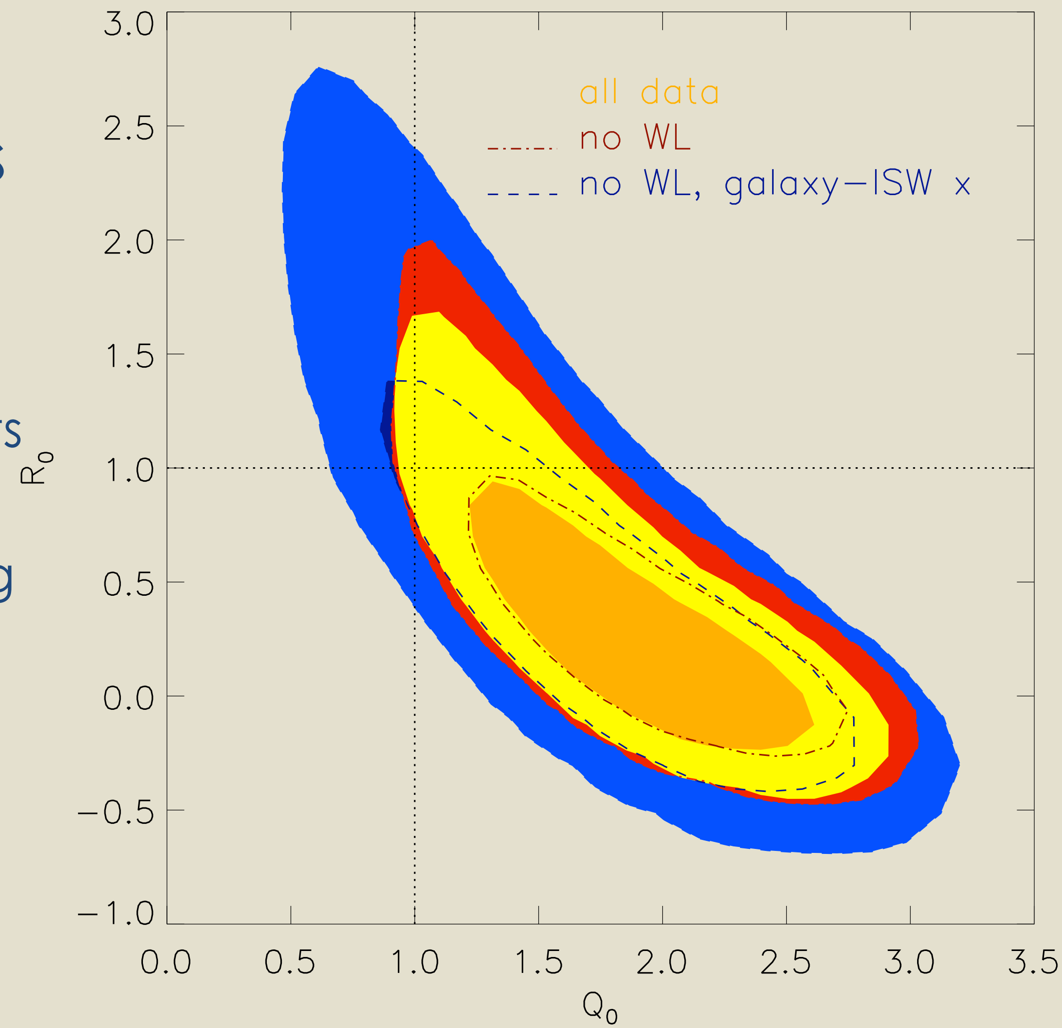
- Emission line (star forming) galaxies
  - Sensitive flux dependency has significant implications for survey depth (Geach et al 09)



Song et al 2010

Current constraints

- WMAP, SDSS LRG auto and ISW-x correlations, COSMOS lensing, Union SN1a
- ISW and ISW-galaxy correlations drive constraints
- Principal degeneracy along Q(1+R)/2
- FoM ~ 0.02



Bean & Tangmatitham PRD 2010

Describing future constraints

- 2-point autocorrelation between observables X and Y using Limber approximation

$$C_l^{XY} = \int_0^{\chi_\infty} \frac{d\chi}{\chi^2} W_X(\chi) W_Y(\chi) T_X(k_l,\chi) T_Y(k_l,\chi) \Delta_R^2(k_l),$$

Comoving distance

$$\chi = \int_a^1 \frac{dt}{a}$$

Window function for observable X

(sensitive to homogeneous Background)

Transfer function for observable X

(sensitive to growth history)

Primordial power spectrum for k=l/χ

Combining observations

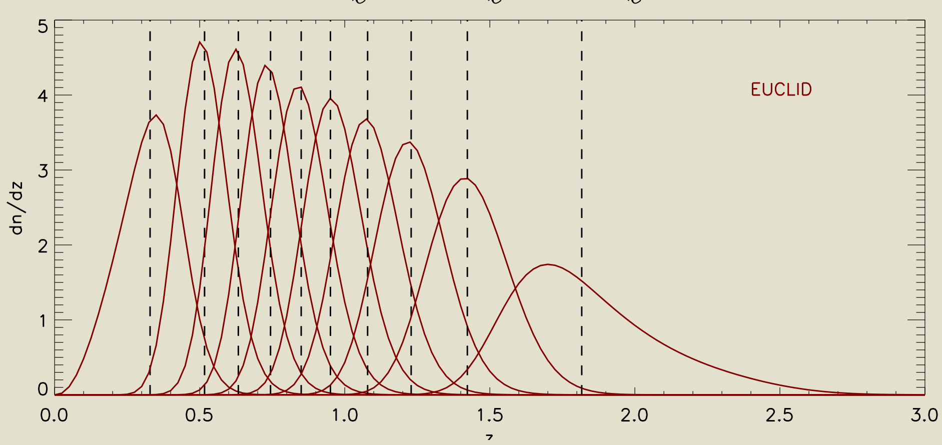
- ISW, lensing, galaxy position and peculiar velocity measurements have distinct dependence on ϕ and ψ

- Cross-correlations could be key to improving constraints
  - Between observables: helps remove bias sensitivity

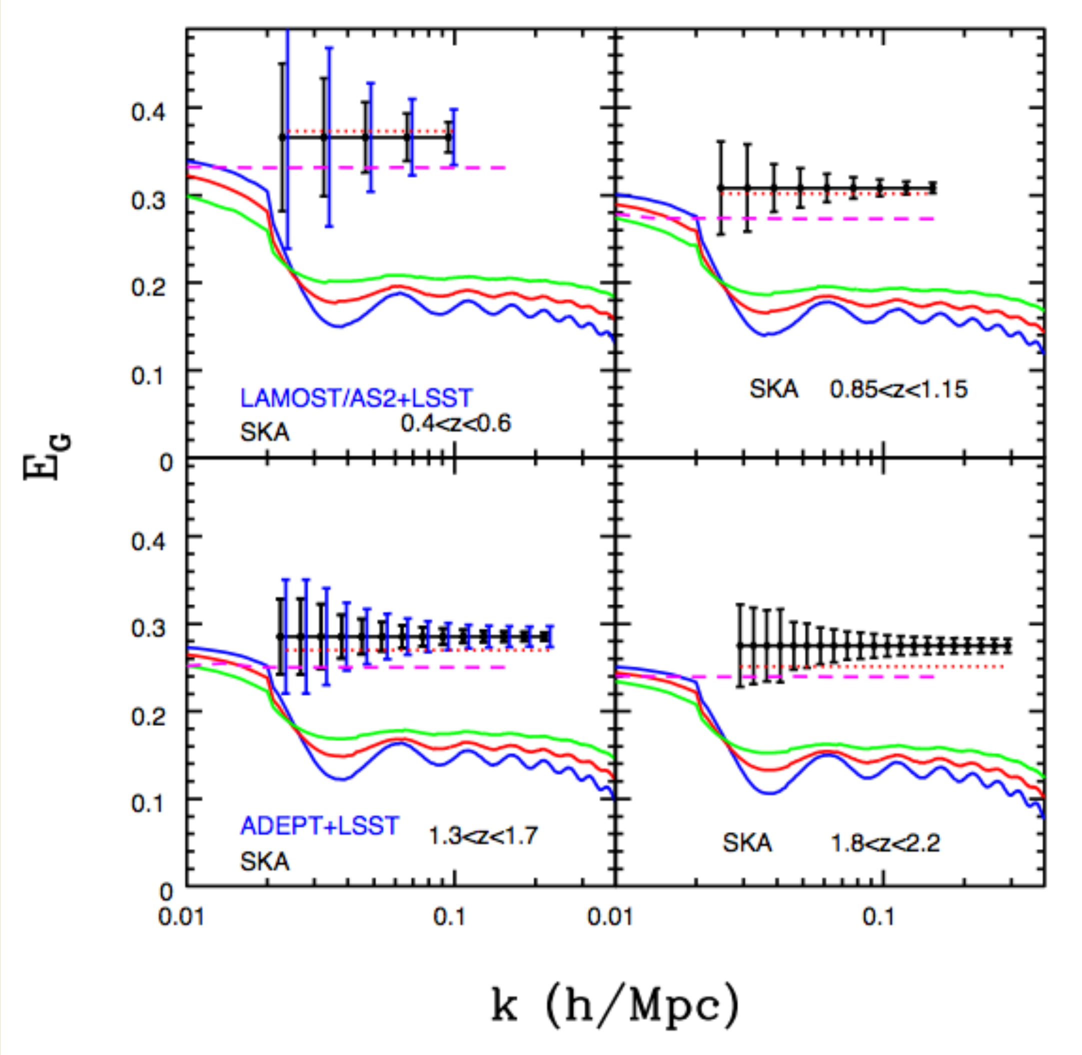
$$E_g \sim \frac{C_l^{g\kappa}}{C_l^{g\Theta}}$$

  - Between z bins: tomography helps probe growth evolution

$$C_\ell^{g_1 g_2}, C_\ell^{g_1 \kappa_2}, C_\ell^{\kappa_{N_{ph}} \kappa_{N_{ph}}}$$



Distinguishing between modified gravity and Λ



Zhang, Liguori, RB, Dodelson PRL 2007

$$E_g \sim \frac{C_l^{g\kappa}}{C_l^{g\Theta}}$$

GR

DGP

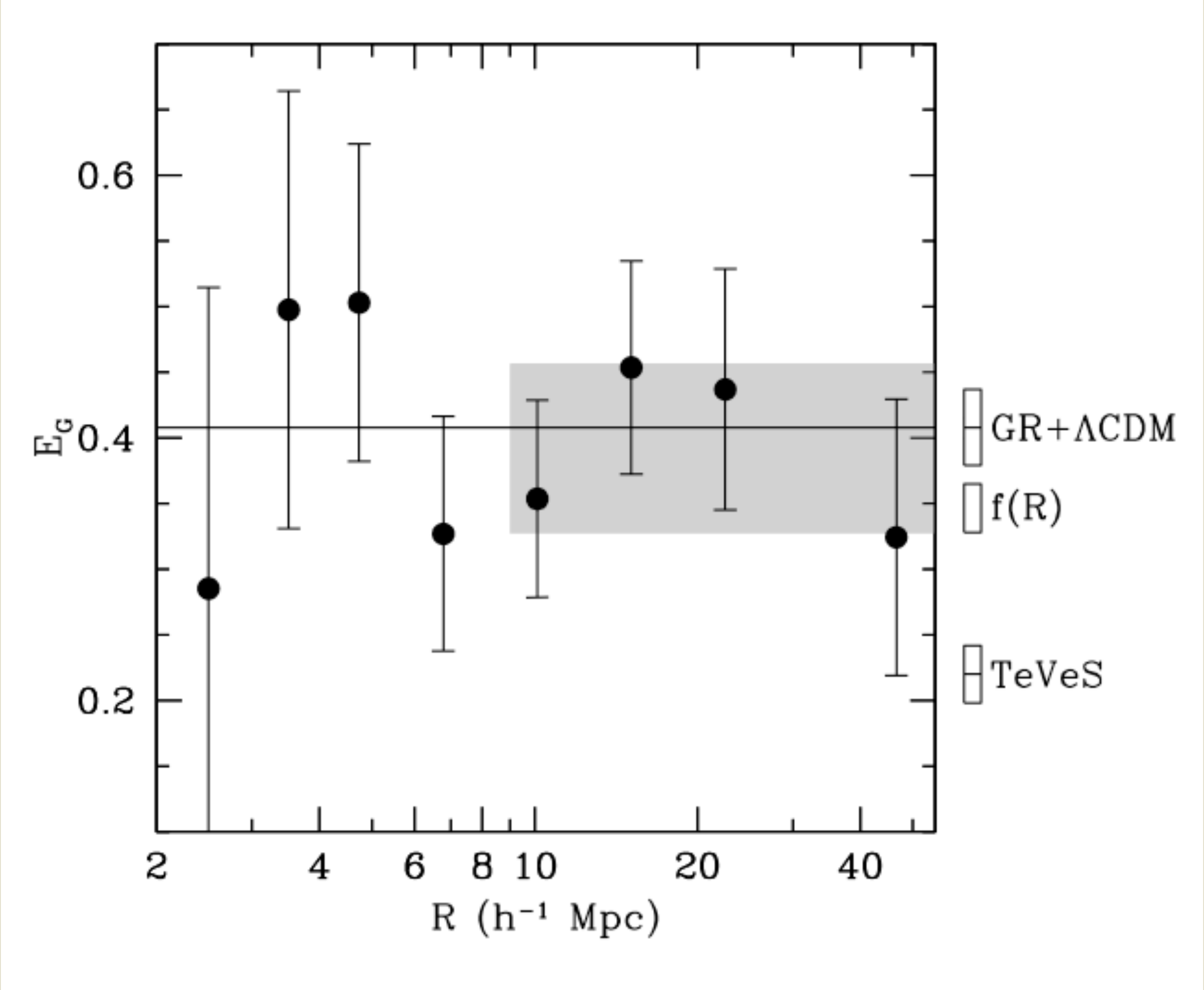
f(R)

TeVeS K=0.1

TeVeS K=0.09

TeVeS K=0.08

Recent proof of principle with SDSS LRG data



Reyes et al Nature 2010

Modeling systematics

- Bias
  - K and z dependent bias interpolated on Nk x Nz bins
    - Galaxy position
    - Peculiar velocity due to evolution bias (Percival & Schafer 07)
    - Cross correlations
- Nonlinearities
  - Conservative approach: make cuts on linear scales (Rassat et al 08)

$$l^i_{max} = k_{max}(z_i)\chi(z_i)$$

  - Or assume Zel'dovich approx. holds & use Smith et al fit
- Intrinsic alignments (Bean, Bridle, Kirk, Laszlo in prep)
  - Additional contributions to lensing and galaxy correlations (Bernstein 09)

$$C_{\kappa\kappa} \rightarrow C_{\kappa\kappa} + C_{I\kappa} + C_{\kappa I} + C_{II}$$
$$C_{g\kappa} \rightarrow C_{g\kappa} + C_{gI}$$

  - Include bias uncertainties in all terms (Joachimi and Bridle 09)
- Photometric redshifts
  - Redshift uncertainty, bias and catastrophic errors

Fisher survey and cosmological parameters

- Fisher matrix analysis

$$F_{ij} = \frac{\partial t_a}{\partial p_i} Cov^{-1}_{ab} \frac{\partial t_b}{\partial p_j}$$

$$\mathbf{p} = \{\Omega_b, \Omega_c, H_0, \tau, w_0, w_a, Q_0, Q_0(1+R_0)/2, n_s, \sigma_8; b_g^{ij}, r_g^{ij}\}$$

$$\mathbf{t} = \{C_\ell^{TT}, C_\ell^{TE}, C_\ell^{EE}, C_\ell^{Tg_1}, ..., C_\ell^{Eg_1}, ...C_\ell^{g_1g_1}, C_\ell^{g_1g_2}, ..., C_\ell^{\kappa_{N_{ph}}\kappa_{N_{ph}}}\}$$

- Including/excluding ell cut at breakdown of linearity

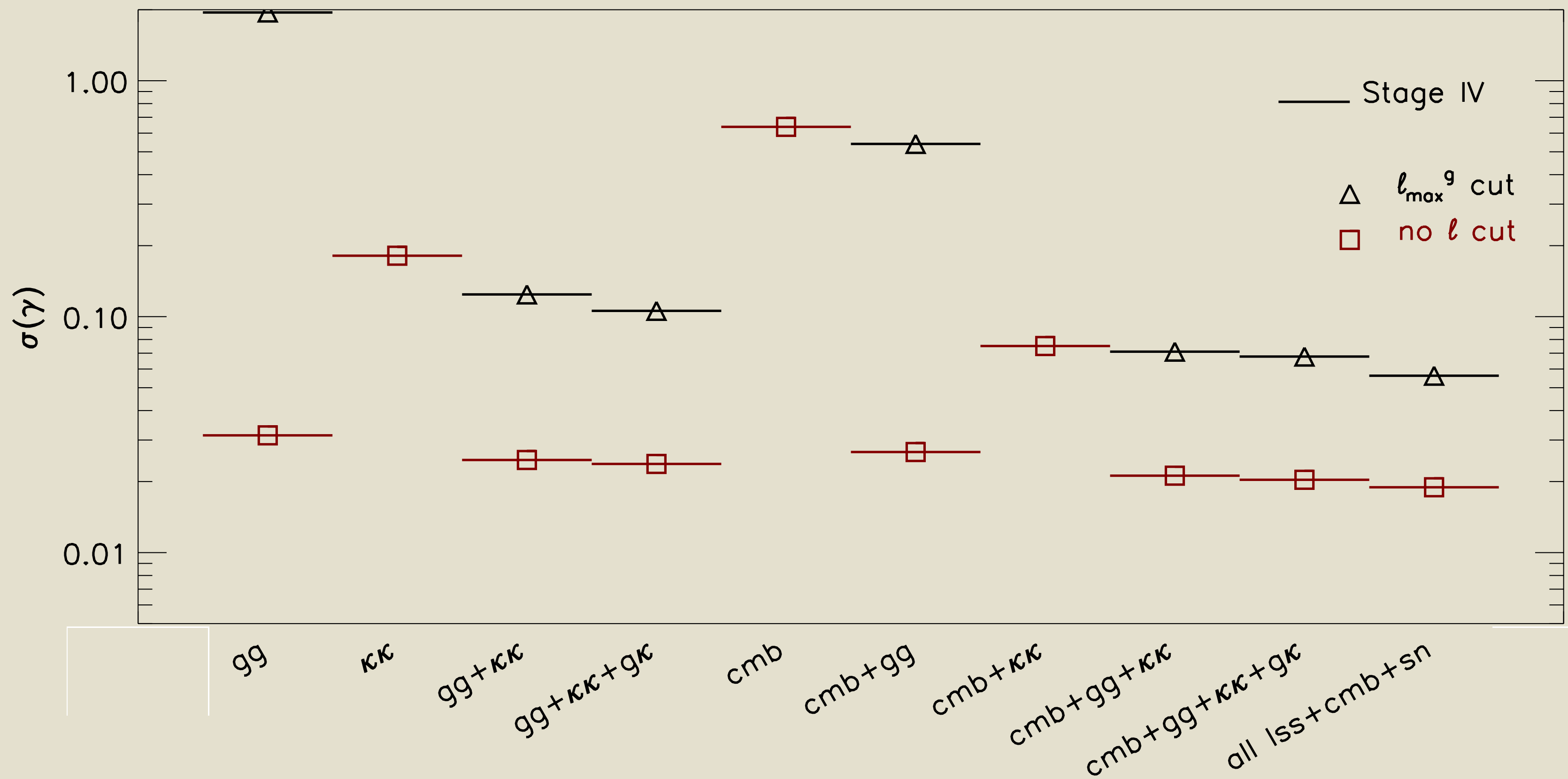
Survey Parameters	Planck		
ν(GHz)	100	143	217
f_{sky}	0.8		
θ_{FWHM}(arc min)	10.7	8.0	5.5
$\sigma_T(\mu K)$	5.4	6.0	13.1
$\sigma_E(\mu K)$	-	11.4	26.7

Survey Parameters	Stage III	Stage IV
σ_{ph}	0.07	0.05
$\sqrt{2}z_0$	0.8	0.9
N_{ph}	5	10
z_{min}	0.001	0.001
z_{max}	3	3
n_g^{2d} (per sq. arcmin)	10	35
σ_γ	0.23	0.35
f_{sky}	0.12	0.50

Parameter	Value
Ω_b	0.0227
Ω_m	0.1107
H_0	71.3851
τ	0.0856
w_0	-1
w_a	0
Q_0	1
$Q_0(1+R_0)/2$	1
n_s	0.9693
σ_8	0.80125

FoM 1: Error in γ

$$\Delta_\gamma(a) = \Delta_{\gamma 0} a^3$$

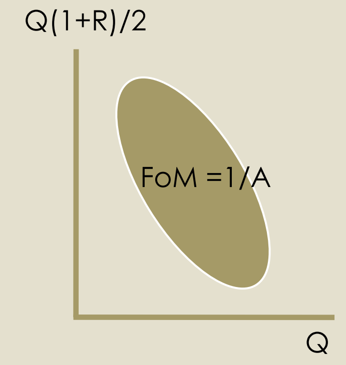


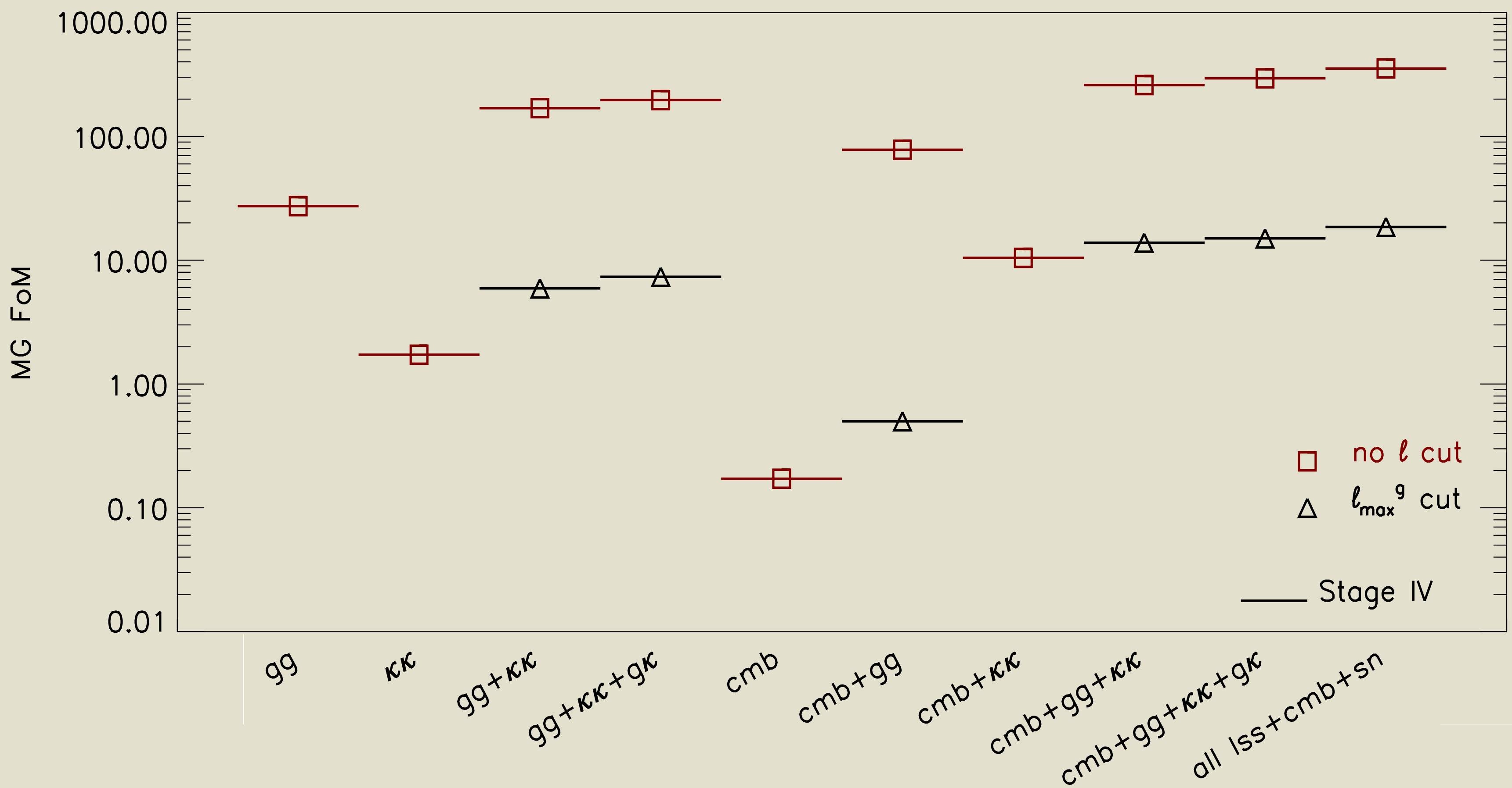
Bean,Laszlo, Muller in prep

FoM 2: Q vs Q(1+R) error ellipse

$$k^2\phi = -4\pi G Q a^2 \rho \Delta$$

$$\psi = R\phi$$





Bean,Laszlo, Muller in prep

Thoughts

- Measuring the growth history is key to testing for large scale deviations to GR, (but also for measuring neutrino masses, primordial non-Gaussianity).
  - WFIRST can do more than measure w0/wa. This is an important opportunity, not just a twofer.
  - Should consider this in assessing WFIRST. It's not just piggy-back science
- Multiple complementary measures of growth are important to break degeneracies
  - how does WFIRST fit in with EUCLID, BiOSS/BigBOSS, LSST, others?
- Systematics modeling to be factored in on FoM calculations
  - Characterizing systematics is going to be key (need to decide how to do this for mature and nascent approaches)
- Couple of different figures of merit (do we look at both or just one?):
  - γ simple phenomenological,
  - R/Q more info. More direct tie to theory.

EXTRA SLIDES

Modifications to GR

- Large scale modifications to GR an active area of theoretical investigation
  - GR

$$S = \int d^4x\sqrt{-g}\frac{1}{16\pi G}R$$

  - f(R) gravity

$$S = \int d^4x\sqrt{-g}\frac{1}{16\pi G}\left(R + f_2(R)\right)$$

$$\frac{\ddot{a}}{a} - H^2 f_R + \frac{a^2}{6}f + \frac{3}{2}H\dot{f}_R + \frac{1}{2}\ddot{f}_R = -\frac{4\pi G}{3}(\rho + 3P)$$

  - Higher dimensional gravity e.g. DGP

$$S = \int d^5x\sqrt{-g^{(5)}}\frac{1}{16\pi G^{(5)}}R^{(5)}$$

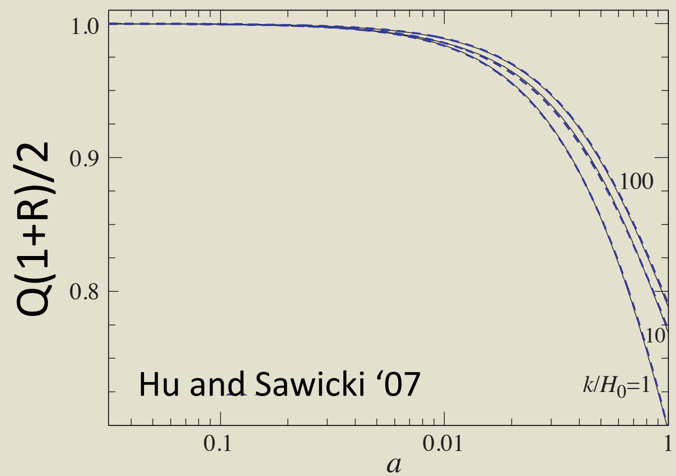
$$H^2 - \frac{H}{r_c} = \frac{8\pi G}{3}\rho$$

Theories can be described in this way

- DGP: Scale independent modifications

$$\beta(a) = 1 - \frac{2H(a)^2 l_c^2}{2H(a)l_c - 1} \qquad l_c = \frac{m_p^{(4)2}}{2m_p^{(5)3}}$$

$$Q(a) = 1 - \frac{1}{3\beta(a)} \qquad R(a) = \frac{2}{3\beta(a) - 1}$$



- f(R) gravity : scale dependent modifications

$$Q(a) = \left(1 + \frac{df}{dR}\right)^{-1}$$

$R(a)$ more complicated